Virtual Hand Realism Affects Object Size Perception in Body-Based Scaling

Nami Ogawa*
The University of Tokyo

Takuji Narumi†
The University of Tokyo / JST PREST

Michitaka Hirose‡
The University of Tokyo

Abstract

How does the representation of an embodied avatar influence the way in which one perceives the scale of a virtual environment? In virtual reality, it is common to embody avatars of various appearances, from abstract to realistic. It is known that changes in the realism of virtual hands affect the self-body perception, including body ownership. However, the influence of self-avatar realism on the perception of non-body objects has not been investigated. Considering the theory that the scale of the external environment is perceived relative to the size of one's body (*body-based scaling*), it can be hypothesized that the realism of an avatar affects not only body ownership but also the fidelity of the avatar with respect to our own body as a metric. Therefore, this study examines how avatar realism affects perceived object sizes as the size of the virtual hand changes. In the experiment, we manipulate the level of realism (realistic, iconic, and abstract) and size (veridical and enlarged) of the virtual hand and measure the perceived size of a cube. The results show that the size of the cube is perceived to be smaller when the virtual hand is enlarged compared to when it is veridical, indicating that the participants perceive the sizes of objects based on the size of the avatar, only in the case of a highly realistic hand. Our findings indicate that the more realistic the avatar, the stronger is the sense of embodiment including body ownership, which fosters scaling the size of objects using the size of the body as a fundamental metric. This provides evidence that self-avatar appearances affect how we perceive not only virtual bodies but also virtual spaces.

Index Terms: Human-centered computing—Virtual reality

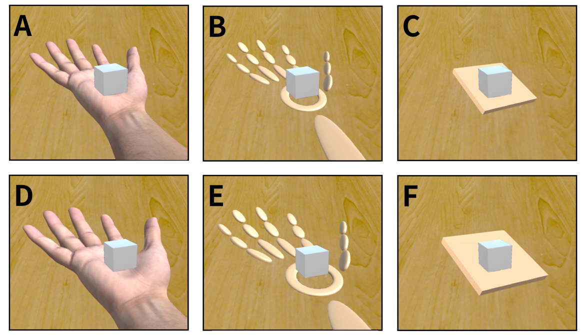

Figure 1: Virtual hands used in the experiment. Participants embodied realistic (A and D; high-realism), iconic (B and E; medium-realism), or abstract virtual hands (C and F; low-realism). The sizes of the virtual hands varied between veridical with the participants' own hands (A–C) and magnified by 1.25 times (D–F).

1 Introduction

The development of body-tracking technologies enables the creation of a digital duplicate of one's own body, an avatar, in virtual environments (VEs). Self-avatars have long been used as entities that perform an *action* in VEs. In particular, avatar hands provide a means of direct manipulation of virtual objects. Contrary to this view, recent studies on avatars have focused more on the aspect of *perception* as a self-body representation. With the emergence of increasingly interactive virtual reality (VR) applications, the identification and analysis of the important effects of avatars on user perceptions are growing in importance.

Indeed, showing virtual hands that properly represent users' real movements improves user experiences in VR, including the sense of embodiment and the feeling of presence [14, 47, 48]. In addition, the appearance of virtual hands influences the sense of embodiment. A realistic virtual human hand elicits a stronger sense of body ownership compared with iconic and abstract hand appearances [1, 22, 28, 58]. Furthermore, a recent study by Schwind *et al.* [45] revealed that the realism of virtual hands could affect how participants combine conflicting visual and haptic signals. However, despite considerable work on the effect of realism on self-body perception, little is known about whether the realism of virtual hands influences how users perceive virtual objects, which is conventionally considered as unrelated to self-body representation. It is necessary to explore what happens to size perception when we embody the different avatars so that the VEs are perceived as precisely as the real environment, especially in scale-sensitive VR applications (e.g., 3D modeling, architecture design, and telemedical practices).

Conventionally, visual space perception has been considered a matter of geometric and optical analysis (e.g., object size is generally considered an intrinsic primary quality of an object). However, recent views emphasize the act of body in space perception [3, 30, 38, 54]: object size perception is affected by the perceived size of the body [2, 7, 23, 49–51]. A notion, called *body-based scaling*, considers that one's own body acts as a perceptual ruler, which individuals use to scale the apparent sizes of objects in their environment [23, 32]. The study by Linkenauger *et al.* supported this notion by showing that increase in the size of one's virtual hand results in decrease in the perceived sizes of objects [23]. Additionally, they found that this effect was specific to participants' virtual hands rather than extraneous hands or a salient familiarly sized object. Similarly, the scaling effect was found to be greater when they experienced a stronger sense of body ownership over the artificial bodies [49, 50].

Considering these studies, it can be hypothesized that the more realistic the virtual hands are, the stronger the sense of body ownership is, which fosters scaling the size of objects using the avatar's body size as a metric. Therefore, we investigate herein the effect of virtual hand realism on the extent to which the size of a virtual object is perceived based on the size of the virtual hand. Our results prove that the less realistic the virtual hands are, the lesser impact the hand size has on the object size perception, indicating that avatar realism affects the way we perceive the virtual objects. This study sheds new light on the importance of avatar representation in a three-dimensional user interface (3DUI) field in terms of how it affects the manner in which we perceive the scale of an object in a VE.

*e-mail: ogawa@cyber.t.u-tokyo.ac.jp
†e-mail: narumi@cyber.t.u-tokyo.ac.jp
‡e-mail: hirose@cyber.t.u-tokyo.ac.jp

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2 Related Work

2.1 Effect of Avatar Realism on Self-body Perception

The well-known experiment of rubber hand illusion (RHI) showed that synchronous visuotactile stimulation elicits body ownership of a fake limb [5]. Inspired by RHI, the report of the virtual hand illusion (VHI) showed that synchrony between visual and proprioceptive information along with motor activity induce an illusion of ownership over a virtual arm [43]. Since those reports, a considerable number of studies has investigated factors influencing the strength of the VHI and how far we can embody virtual avatars of representations different from our own bodies (for review; [14, 15]).

In both RHI and VHI, the closer the avatar appearances are to our own bodies in terms of structural and morphological aspects, the stronger is the sense of body ownership because our semantic memories and knowledge contribute to the shaping of internal models of the body as higher-order, top-down cognitive processes [15]. This holds as long as spatially and temporally synchronous visuotactile or visuomotor stimuli are provided. Argelaguet *et al.* [1] compared realistic (human), iconic (robotic), and abstract (sphere) virtual hands, which provided different degrees of visual realism but possessed the same control mechanism, and showed that the body ownership was higher for the human virtual hand. Although Lugrin *et al.* [27] indicated the presence of the uncanny valley effect [31], in which machine-like and cartoon-like full-body avatars elicit a slightly stronger body ownership than human avatars in full body ownership illusions, reduced avatar realism was confirmed to result in a weaker body ownership in general [1, 14, 15, 22, 28].

Similar to Argelaguet's study [1], most studies investigating the effect of realism used a realistic human hand that appears to be connected to the participant's body by a virtual forearm as the highest level of realism [22, 44, 45, 58]. Non-human hands (e.g., robotic, cartoon, and abstract) [1, 22, 44, 45] or non-corporeal (non-anthropomorphic) objects (e.g., sphere, block, and arrow) [1, 22, 28, 39, 58] have often been used as non-realistic hands. In contrast, current advances in capturing individualized human bodies by photogrammetry methods have motivated the investigation of the impact of personalized avatars, such as a scanned full body, including the individual's clothes [19, 52], as avatars that are closer in appearance to our own bodies than realistic but generic virtual avatars. Personalized avatars improve subjective feelings, such as body ownership, presence, and emotional response, even compared to avatars that are equal in terms of the degree of realism and graphical quality [19, 26, 52]. Nevertheless, equipping personalized avatars is still a time-consuming process. Alternatively, the impact of a personalized hand using video feedback on subjective feelings, performance, and object size estimation has also been investigated [12, 39]. However, interacting with virtual objects through video feedback images is difficult, unlike virtual 3D avatars. Therefore, the manipulations of the levels of realism are often limited to generic appearances, from realistic virtual human limbs to non-corporeal objects, in common VR applications.

While the effect of realism on how users perceive the avatar has been investigated by various measurements, such as body ownership, presence, acceptance, and sense of agency [1, 39, 44], little is known about the effect of realism on how the users perceive the whole virtual world. Schwind *et al.* recently investigated whether the multisensory integration of visual and haptic feedback can be influenced by the appearance of virtual hands among human, robot, cartoon, abstract, and invisible hands [45]. Their results showed that visuo-haptic integration is influenced by the rendering of virtual hands. It indicates that avatar realism changes not only the perception *of* self-body, but also the perception *through* self-body. Still, whether the space perception is affected by realism or not is a hitherto unexplored aspect of avatar representation.

2.2 Effect of Body Representation on Spatial Perception

Our body representations are so plastic and malleable that they can be altered in terms of size, morphology, and semantics through bodily illusions with VR (e.g., VHI [43], full body ownership illusion [29], and manipulation of interpupillary distance (IPD) or eye height) or without VR (e.g., RHI [5] and proprioceptive illusion induced by tendon vibration [17]). The semantic change in one's own body representation, such as gender [46], skin color [13, 35], attractiveness [57], and age [2, 34], leads to behavioral and attitudinal changes on the user through stereotype or memory, which is automatically associated with avatars.

In contrast, the change in the size of body representation is known to influence the external scale perception (i.e., body-based scaling) because the representation of allocentric space is functionally linked to egocentric representations [6]. Various ways of manipulating the size of one's body representations, such as virtual embodiment over an avatar hand [23] or a full-body child avatar [2], manipulation of IPD or eye height [8, 18, 20, 21], and RHI with a barbie doll [51], have been shown to change how one visually perceives the scales of external environments in terms of both size and distance. In VEs, we often embody avatars, whose representation is not identical to one's own body in terms of its size and appearance. This is considered one of the reasons of the well-known phenomena of egocentric distances appearing to be compressed in VEs [25, 40]. Indeed, the egocentric distance estimation becomes accurate when the self-avatar is displayed, especially if the avatar is self-animated in real time [20, 30, 36, 41]. Furthermore, the impoverishment of avatar fidelity (e.g., showing either full body avatar, only joint locations, or end-effector) compromises the improvements of the accuracy of distance estimations in both near field [9] and far distances [42].

The effect of body as a fundamental reference in space perception differs from the mere use of the body in sight as a familiar size cue. Our implicit body representations are rather used to calibrate the perception of the external world [7]. Thus, body ownership is considered an important factor. The influence on the size estimation is eliminated or weakened when body ownership is absent [2, 49–51]. For example, Van der Hoort and Ehrsson [49, 51] induced RHI with artificial dolls. Their results showed that objects and distances were perceived as smaller and nearer for a larger body and vice versa for a smaller body. However, the effect was weakened when body ownership was disrupted, even though the retinal images were the same. Furthermore, the stronger the body ownership illusion, the stronger the effect across participants.

Considering these studies, it can be anticipated that if avatar representation is less likely to be embodied, its fidelity as one's own body representation decreases, resulting in decreased influence on body-based scale perception. However, studies on object size estimation have so far not placed much emphasis on avatar realism. Indeed, previous studies that investigated the effect of perceived body size on object size perception in VE used realistic human avatars [2, 23]. Thus, it is still unknown if the effect is also verified with less realistic but commonly used virtual avatars. Only recently did Jung *et al.* [12] investigate the effect of a personalized hand on object size perception as well as body ownership and presence. They compared generic virtual hands of invariant size and appearance, modeled using three-dimensional computer graphics (3DCG), with hands that were personalized in size and appearance and presented using a video-based chroma key approach. They found that the use of personalized hands not only increased body ownership and presence, but also accuracy in object size estimation compared to generic 3DCG virtual hands. This study supports our view that the closer the avatar hand is to one's own, the easier it can be used in size estimation. In contrast to their study, we are interested in the pure effect of visual realism of virtual avatars on size estimation rather than the personalization effect because hands with various levels of realism are commonly used in current VR systems.

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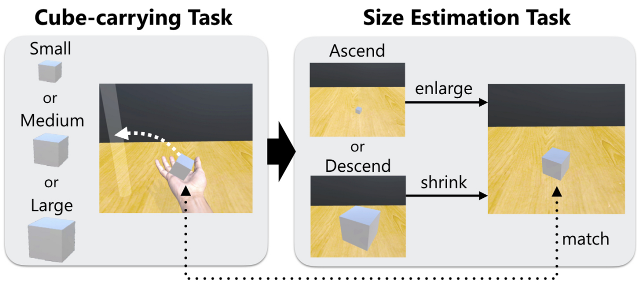

Figure 2: Each trial consisted of a cube-carrying task, where the participants carried a virtual cube to a target cylinder with a virtual hand, and a successive cube size estimation task, where the participants enlarged or shrank a size-adjustable cube using a controller such that its size corresponded to their perception of the cube's size.

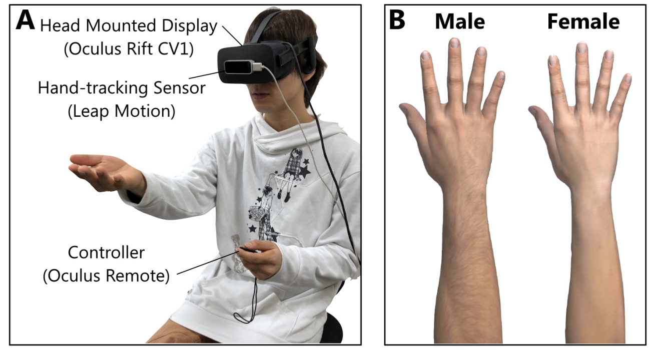

Figure 3: (A) Realistic male and female hands used in the high-realism condition. (B) A participant wearing a head-mounted display with a hand-tracking sensor pushing a controller with his non-dominant hand.

3 EXPERIMENT

The experiment aims to investigate the effect of virtual hand realism on the body-based scaling effect, that is, to what extent the size of a virtual object is perceived based on the size of the virtual hand. The participants performed a cube-carrying task with virtual hands of various sizes and realism levels (see Figure 1) and estimated the size of the cube by scaling a size-adjustable virtual cube (see Figure 2). We hypothesized that the object size is perceived as smaller with the enlarged hand than with the veridical hand for the realistic virtual hand. We also hypothesized that the less realistic the virtual hands are, the weaker the sense of body ownership is, which makes it harder to scale the size of an object based on the size of one's body.

3.1 Participants

A total of 24 individuals (12 males and 12 females; 28.18 ± 8.04 (SD) years old) participated. They were recruited through social media. All participants were naive as to the true purpose of the experiment, had normal or corrected-to-normal vision, and were right-handed. We did not recruit participants with glasses because they tend to have difficulty in correctly wearing a head-mounted display (HMD). Seven participants had no previous experience with VR; 13 had limited previous experience; and four were familiar with VR. The participants signed an approved statement of consent and they were compensated with an Amazon gift card amounting to approximately $10.

3.2 Apparatus

Figure 3A shows the experimental setup. The experimental apparatus includes a Windows-based computer, a motion sensor (Leap Motion Controller), an HMD set (Oculus Rift CV1), and a controller (Oculus Remote). The experimental program has been developed using Unity 3D. The experimental scene is designed as a simplified room composed of a wooden table, a white cube, and a translucent cylinder to eliminate the possibility of participants using a specific strategy for size estimation, such as a direct comparison with the features of textures or objects.

We adopted the Leap Motion Controller as a hand-tracking device in the same manner as in the previous studies on avatar realism [1, 22, 44, 45]. It could track the forearm, hand, and fingers of the users at distances of up to 1 m. It automatically detected the hand size for each participant. Its estimations deviated from the actual positions by 1.2 mm on average [53]. Therefore, we considered it to have sufficient accuracy and robustness for scaling and tracking hands for the purpose of this study. To further verify its accuracy and robustness, we recorded the sensor-estimated hand sizes of ten individuals (i.e., five males and five females; 25.14 ± 6.59 (SD) years old) and measured the size of individuals' actual hands by a ruler prior to the experiment. As a measurement, we used the width of the palm across four bottom knuckles and the distance from the middle fingertip to the bottom knuckle. As for accuracy, the measured values by a ruler (palm width (cm): $M = 8.31, SD = 0.89$, middle finger length (cm): $M = 7.94, SD = 0.76$) and the estimated values by a sensor (palm width (cm): $M = 8.27, SD = 0.56$, middle finger length: $M = 8.09, SD = 0.64$) were significantly correlated (palm width: $r = 0.95, p < .001$, middle finger length: $r = 0.96, p < .001$), indicating a reasonable agreement. As for robustness, we calculated the standard deviations (SD) across 100 times of measurements by a sensor per individual and calculated the mean of the SD across individuals (palm width (cm): $M = 0.36$, middle finger length (cm): $M = 0.49$). Given that the actual one-time measured values by a ruler also have measurement errors, we consider that the sensor detects the hand size and sufficiently shows the veridical size of the virtual hand for each individual in the experiment. Note that in the experiment, we were interested in the relative values across conditions in the virtual setup rather than in the comparison between real and virtual environments.

3.3 Design

The experiment followed a $3 \times 2 \times 3 \times 2$ factorial design. The independent variables were avatar realism (*high, medium, and low*), hand size (*veridical and enlarged*), cube size (*small, medium, and large*), and adjustment direction (*ascending and descending*). All variables were within-subject.

3.3.1 Conditions

Avatar Realism We used three types of hand appearance with different levels of realism, as shown in Figure 1. The appearances were chosen based on the study by Argelaguet *et al.* [1] using a realistic male virtual hand, including a forearm, an iconic virtual hand representing a simplified robotic hand, and an abstract virtual hand formed as a sphere. We slightly modified its appearance based on our study context. First, we used a realistic female virtual hand for female participants because the study by Schwind *et al.* [44] revealed that women feel less presence and perceive more eeriness using virtual male hands. They also suggested providing male and female hands if human avatars are desired. Thus, we chose to use male virtual hands for male participants and female virtual hands for female participants. Second, we used a board instead of a sphere because we adopted a cube-carrying task that followed a realistic physical simulation as far as possible. Lastly, we decided to change the skin colors of the iconic and abstract hands to avoid any influence of color contrast on size perception.

As for the control scheme, the high- and medium-realism hands used the same skeleton rig with the same number of degrees of freedom, but the low-realism hand moved based only on the position and

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rotation of the participant's palm. In contrast, all hand models used the same collision-detection surfaces, which corresponded to the surfaces of the realistic hand. This implementation led to a somewhat unnatural situation for the low-realism hand, i.e., the participants could carry cubes on transparent fingers. Nevertheless, we assured that all the virtual hands maintained the same functionality in spite of their different appearances so as to avoid any influence of the functionality on body ownership and object size estimation.

The three representations are summarized as follows:

Realistic hand (High realism): realistic male and female virtual hands, including a forearm (Figure 1 A & B; Figure 3 B). 3D models were obtained from the Leap Motion Software Development Kit (SDK).

Iconic hand (Medium realism): a non-human hand equipped with an ellipsoid representing bones and a torus representing the palm (Figure 1 C & D). 3D models were obtained from the Leap Motion SDK.

Abstract hand (Low realism): a non-anthropomorphic board with the length and width equal to the participant's palm and with 1-cm thickness (Figure 1 E & F). The 3D model was created using Unity.

Hand Size In the *veridical* condition, the virtual hand was of the same size as the hand size of each participant (see subsection 3.2). In the *enlarged* condition, the virtual hand was larger than in the veridical condition by a factor of 1.25. The center point of scaling was the center of the palm; hence, the reaching ability and the spatial congruency between proprioception and vision did not change from the veridical hand. The rationale for the value of 1.25 is as follows: previous studies on body-based scaling used a quarter [51], half [2, 23, 51], or doubled [51] size of an artificial or virtual body. Nevertheless, we were interested in the effect of change in hand size on object size perception, which is a likely occurrence in common VR systems. According to our hand anthropometric data of the palm width (male: $M = 8.94$, $SD = 0.44$ and female: $M = 7.66$, $SD = 0.23$; see subsection 3.2), Jung *et al.*'s [12] data (male: $M = 14.88$, $SD = 1.37$ and female: $M = 11.00$, $SD = 0.43$), and Gordon *et al.*'s [11] data (male: $M = 9.04$, $SD = 0.43$ and female: $M = 7.95$, $SD = 0.38$), the male to female ratios roughly varied from 115% to 135%. Furthermore, men whose hand sizes were below or over 2 SD of the mean value, who accounted for 5% of the total, had approximately 20% smaller or larger size to the mean based on Jung *et al.*'s data [12]. In addition to these gender and individual differences, differences by race and age also existed. Therefore, we considered that the enlargement of the hand size by a factor of 1.25 is a likely situation.

Cube Size The sizes of the cubes that were carried by the participants were randomly selected as any of *small* (5 cm), *medium* (7.5 cm), or *large* (10 cm) for each trial.

Adjustment Direction The size-adjustable cube used by the participants to report their size estimations appeared as either 1 cm (*ascending* series) or 15 cm (*descending* series), which are typically used in the method of adjustment to eliminate the anchoring effects.

3.3.2 Measurements

Object Size Estimation As shown in Figure 2, each trial consisted of the cube-carrying task, followed by the cube size estimation task. In the cube-carrying task, the participants carried virtual cubes with the virtual hand. In the successive cube size estimation task, the participants could continuously enlarge or shrink the scale of the size-adjustable cube by pushing the controller's button, such that its perceived size corresponded to the size of the cube that they had carried only previously. For each trial, the ratio of the estimated cube size to the actual size of the carried cube was recorded. Our experimental protocol for the cube size estimation task was similar to that used by Jung *et al.* [12]. The difference was that the virtual hand was displayed while estimating the cube size in the previous work, while it was not in the present study. We did not show the virtual hand to avoid any possibility of the participants estimating the cube size by inference. We expect that the cube size may be directly estimated by comparing the viewed size of the virtual hand with the size of the cube.

Table 1: Questionnaire items to measure the sense of embodiment based on [10]. Items in italic are control questions.

Subscale	Question
Ownership	1) I felt as if the virtual hand was my hand.
	2) *It felt as if the virtual hand I saw was someone else.*
	3) *It seemed as if I might have more than one hand.*
Agency	4) It felt like I could control the virtual hand as if it was my own hand.
	5) The movements of the virtual hand were caused by my movements.
	6) I felt as if the movements of the virtual hand were influencing my own movements.
	7) *I felt as if the virtual hand was moving by itself.*
Location	8) I felt as if my hand was located where I saw the virtual hand.
	9) *I felt out of my body.*

Questionnaire The subjective evaluation of embodiment for a virtual hand was assessed through a questionnaire. Although we were interested in body ownership in particular, we measured the sense of embodiment [14], which consists of body ownership (i.e., one's self-attribution of a body), sense of agency (i.e., the feeling of control over actions and their consequences), and sense of self-location (i.e., one's spatial experience of being inside a body). The rationale for this is we consider that measuring the comprehensive effect of realism on user perception is important for exploiting the insights for VR designers or developers. We used Gonzalez-Franco and Peck's embodiment questionnaire [10], but omitted items that were not applicable to our study context. As a result, the questionnaire consisted of nine items and three subsets of questions: body ownership (Ownership), agency and motor control (Agency), and body location (Location) (see Table 1). Each response was scored on a seven-point Likert scale (-3 = strongly disagree; 3 = strongly agree). The evaluation was performed for each avatar realism, and the size of the virtual hand was not considered.

3.3.3 Hypotheses

Our hypotheses were:

- **H1** The object size is perceived to be smaller with the enlarged virtual hand than with the veridical virtual hand when the virtual hand is realistic.
- **H2** The less realistic the virtual hands, the weaker the sense of body ownership.
- **H3** The less realistic the virtual hands, the less the impact of changes in hand size on the object size estimation.
- **H4** The participants with higher scores of body ownership tend to perceive the object size as smaller when the virtual hand is enlarged.

H1 is hypothesized based on the previous studies showing that object size perception is affected by the perceived size of the body [2, 7, 23, 49–51], although these did not explore the case of a change in body size as small as 1.25 times. **H2** is hypothesized based on a number of research showing that the reduction in realism attenuates body ownership [1, 22, 39, 44, 45, 58], although the presence of the uncanny valley effect is indicated [27]. **H3** is the main interest in this study, which is derived from **H1** and **H2**. **H4** is hypothesized based on Van der Hoort and Ehrsson's studies [49, 50], although they used visuotactile stimuli without VR, and aims to validate that body ownership is intermediate between the avatar realism and the body-based scaling effect.

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3.4 Procedures

3.4.1 Trial Flow

The experimental flow of each trial is described below. As explained in the 3.3.2 section, each trial consisted of a cube-carrying task, followed by a cube size estimation task. In the cube-carrying task, the participants carried cubes to the position of the target cylinder using their dominant virtual hand. The participants were instructed to carry the virtual cube as quickly as possible. The sizes of the carried cubes were any of *small*, *medium*, or *large* for each trial. The positions at which the cubes appeared and those of the cylinders were randomly chosen for each trial, such that they remained within the participants' reach. The cube-carrying task allowed sufficient time to remember the sizes of the cubes in a natural situation. Therefore, we did not measure the performance such as accuracy and the time taken for task completion. Nonetheless, we observed that the cube-carrying task in each trial took approximately 15 s. The cylinder, the cube, and the virtual hand disappeared when the participants successfully finished carrying the cube. Then, the cube size estimation task was performed, wherein the size-adjustable virtual cube with size of either 1 cm (*ascending* series) or 15 cm (*descending* series) appeared on the table for each trial. This appeared at a fixed position for all trials, but at a random orientation. The sizes of the cubes were adjusted, such that their sizes perceptually corresponded to the size of the cube carried by the participants immediately before. The participants could continuously enlarge and shrink this cube with a precision of 1 mm by pressing the up and down buttons on the controller held by their non-dominant hand. They could also rotate the orientation of the cube by pressing the left and right buttons of the controller, if needed. The estimated size of the cube can be considered to represent the perceived size of the carried cube. The virtual hands were not displayed during the cube size estimation task. Once the participants pressed the answer button, the screen turned black and shifted to the cube-carrying task of the next trial, although it was possible to freely adjust the enlargement/shrinkage until the OK button was pressed. We did not set a particular time limit, but the cube size estimation task in each trial took approximately 5 s.

3.4.2 Overall Flow

The overall flow of each experiment is described below. At the beginning, the participants read and signed the experiment consent form. After the explanation of the procedures, including instructions for using the controller, each participant was asked to wear the HMD and adjust the interpupillary distance of the lenses by moving a slider, such that they could clearly see the image. While they wore the HMD, they were unable to see their own real hands. Instead, they could see their virtual hand in the position where their real dominant hand was. The rest of the body, including a non-dominant hand, was invisible in the VE. Their non-dominant hands were holding the controllers placed on their laps during the experiment.

Six unique types of trials (three cube sizes $\times$ two adjustment directions) were successively performed for each hand representation. The successive six trials with the same hand representation were conducted in a random order for each of the six hand representations (three avatar realisms $\times$ two hand sizes). These 36 unique trials constituted a block, and there were three blocks. The order of appearance of the hand representation was randomized in each block. A total of 108 trials per participant were conducted.

A question from the questionnaire and a slider with numbers from -3 to $+3$ were displayed in the VE after all the trials were completed. The questionnaire was shown both in English (original) and in Japanese (translated) at the same time. The participants could see their dominant virtual hand and freely interact with a virtual cube. They were instructed to assess their impressions of the observed virtual hand, whose appearance was at any of the three different levels of realism and whose size was veridical to the participant's own hand. Once they answered the question regarding the observed

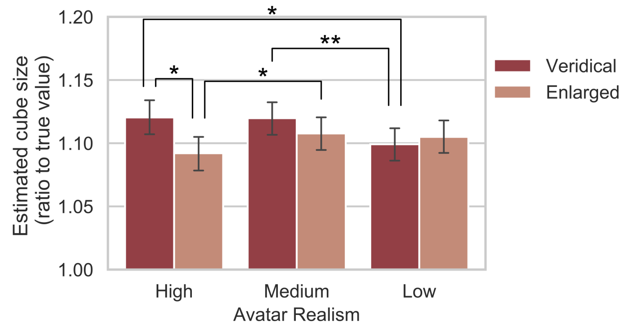

Figure 4: Average estimated cube size as a ratio compared to the true size according to avatar realism and hand size. Error bars indicate the SE. *: $p<.05$, **: $p<.01$.

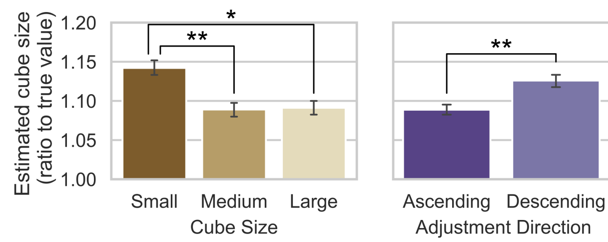

Figure 5: Average estimated cube size as a ratio compared to the true size according to cube size (left) and adjustment direction (right). Error bars indicate the SE. *: $p<.05$, **: $p<.01$.

virtual hand, the appearance of the hand changed to a different level of realism, while the question remained the same. After they answered the same question in the questionnaire for all three types of virtual hands, the next question was shown, which was chosen from among the nine items in a randomized order. The participants were instructed to take off the HMD after the completion of the questionnaire. Finally, they filled up a demographic questionnaire. The whole experiment took approximately 1 h to complete.

4 Results

The data from two participants were excluded from the analysis because one male participant did not finish the experiment owing to fatigue or drowsiness, and one female participant consistently used the wood grain pattern as an absolute metric for size adjustment. Thus, we used a total of 22 data sets for the analysis that follows. ANOVA analyses were conducted when the normality assumption (Shapiro–Wilk's Normality test) was not violated ($p > .05$). When the sphericity assumption was violated (Mauchly's sphericity test), the degrees of freedom were corrected using the Greenhouse–Geisser correction. In addition, η_p^2 were provided for the quantitative comparison of the effect sizes. Finally, Tukey's post-hoc tests ($\alpha = .05$) were conducted to check the significance for the pairwise comparisons of the parametric data. When the normality assumption was violated or the measurement did not use continuous variables, a Friedman test was conducted followed by a post-hoc Wilcoxon signed rank test. For multiple post-hoc comparisons, the Holm correction was applied for non-parametric data. We report only the significant differences for ANOVAs and post-hoc tests ($p < .05$).

4.1 Object Size Estimation

We statistically tested the ratio of the estimated cube size to the actual size of the carried cubes to examine whether the perceived size of the cubes was influenced by the avatar representations. For data

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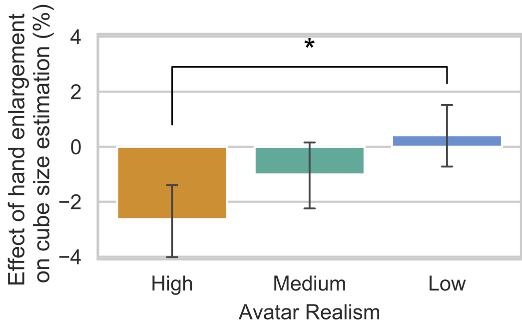

Figure 6: Ratio of the average size estimation in the enlarged hand size condition normalized by the corresponding value in the veridical hand size condition according to avatar realism (percentage deviation from 100 %). Error bars indicate SE. *: p<.05

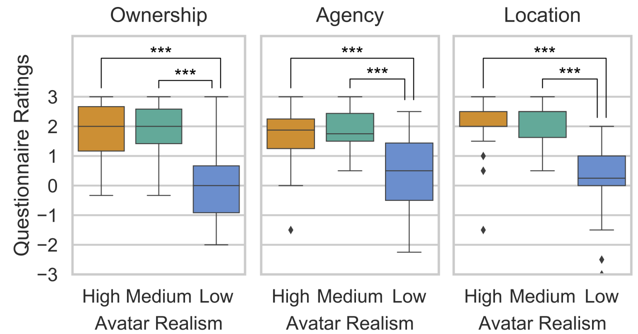

Figure 7: Box plots of the perceived ownership (left), agency (center), and location (right) for each avatar realism level obtained through the questionnaires (from 3 to +3). ***: p<.001

preprocessing, the data under/over 3 SD for each participant were excluded as outliers, resulting in data for 1 out of 108 trials being removed for eight participants. Next, the average value of three repetitions for each unique combination of conditions (36 combinations in total) was used in the analysis for each participant. Finally, four-way ANOVA analyses with repeated measures were conducted considering the within-group factors of avatar realism (three levels: *high, medium, and low*), hand size (two levels: *veridical and enlarged*), cube size (three levels: *small, medium, and large*), and adjustment direction (two levels: *ascending and descending*).

As shown in Figure 4 and Figure 5, ANOVA revealed the significant main effects of hand size [$F(1,21) = 8.32$, $p < .01$, $\eta_p^2 = 0.28$], cube size [$F(1.26,26.53) = 9.73$, $p < .01$, $\eta_p^2 = 0.32$], and adjustment direction [$F(1,21) = 8.32$, $p < .01$, $\eta_p^2 = 0.28$]. ANOVA also showed a significant two-way interaction effect between hand size and avatar realism [$F(1.74,36.50) = 5.66$, $p < .01$, $\eta_p^2 = 0.21$]. An interaction effect existed between only the hand size and the avatar realism; hence, the effects of the cube size and the adjustment direction can be interpreted individually. As we observed both the main effect of the hand size and an interaction effect between the hand size and the avatar realism, we conducted Tukey's post-hoc tests for each realism level and hand size (see Figure 4). When comparing the value for each realism level, the sizes of the cubes were estimated as significantly smaller in the case of the enlarged hand size ($M = 1.09$, $SE = 0.02$) compared with the case of the veridical hand size ($M = 1.13$, $SE = 0.02$) only in the high-realism condition ($p < .05$). This result supports **[H1]**: the object size is perceived to be smaller with the enlarged hand than with the veridical hand when the hand is realistic. In contrast, the cube sizes were estimated as significantly smaller with the low-realism avatar ($M = 1.10$, $SE = 0.02$) compared with the medium- ($M = 1.12$, $SE = 0.02$; $p < .01$) and high-realism avatars ($M = 1.13$, $SE = 0.02$; $p < .05$) for the veridical hand size condition and in the high-realism avatar ($M = 1.09$, $SE = 0.02$) compared with the medium-realism case ($M = 1.11$, $SE = 0.02$) for the enlarged hand size condition ($p < .05$). Next, as we observed the main effect of the cube size, we conducted Tukey's post-hoc tests. The result showed that the small cube size ($M = 1.15$, $SE = 0.02$) was perceived as larger than the true size when compared to the medium ($M = 1.09$, $SE = 0.02$; $p < .01$) and large cube sizes ($M = 1.09$, SE =0.02; $p < .05$) (see Figure 5, left). Note that cube sizes were estimated as larger than their true values for all conditions. The significant main effects of the adjustment direction ($p < .01$) showed that the cube size was perceived as smaller in ascending ($M = 1.09$, $SE = 0.01$) compared to the size in descending series ($M = 1.13$, $SE = 0.02$) (see Figure 5, right).

The results of the post-hoc analysis of four-way ANOVA indicated that hand enlargement influenced the estimated cube size only in the high-realism condition. This indirectly supported **[H3]**: the less realistic the virtual hands, the less the impact of the changes in hand size on the object size estimation. To directly test **[H3]**, we calculated the percentage ratio of the estimated cube size in the enlarged hand size condition normalized by the corresponding value in the veridical hand size condition for each degree of avatar realism (see Figure 6). The values indicate the extent to which the cube size is perceived as smaller or larger for enlarged vs. veridical virtual hands for each level of avatar realism. We conducted a one-way ANOVA analysis considering the within-group factors of avatar realism to further examine whether the effect of hand enlargement on estimated cube size was different among the three levels of realism. The ANOVA showed a significant effect for avatar realism [$F(1.78,37.29) = 5.72$, $p < .01$, $\eta_p^2 = 0.21$] and Tukey's post-hoc tests showed that the value was significantly smaller for high realism than for low realism ($p < .05$). This result supports **[H3]**.

4.2 Questionnaire

To test **[H2]**: the less realistic the virtual hands, the weaker the sense of body ownership; the subjective ratings of the questionnaire were analyzed. Agency, ownership, and location ratings were aggregated and averaged (answers for control items were inverted) to compute the scores for each avatar realism per participant, as introduced in the original study containing the questionnaire [10]. We used different avatars for different genders in the high-realism condition; hence, we examined the scores by considering the factor of gender as well as avatar realism. We applied an aligned-rank transform (ART) to the data because of the non-parametric nature of the data. The ART procedure allows the use of ANOVA to analyze the interaction effects with the non-parametric data [56]. Two-way repeated-measure ANOVAs with the within-subject factor of avatar realism (three levels: *high*, *medium*, and *low*) and between-subject factor of gender (two levels: *Male* and *Female*) were performed for each subscale. For all subscales, the ANOVA revealed a significant main effect only of avatar realism [Ownership; $F(2,40) = 26.37$, $p < .001$, $\eta_p^2 = 0.57$, Agency; $F(2,40) = 39.92$, $p < .001$, $\eta_p^2 = 0.67$, Location; $F(2,40) = 40.68$, $p < .001$, $\eta_p^2 = 0.67$] (see Figure 7). No interaction effects existed between gender and avatar realism; thus, we conducted post-hoc pairwise comparisons using the Wilcoxon signed-rank test (Holm-corrected) considering the within-group factor of avatar realism for each subscale. The results showed that in all the subscales, the scores were significantly lower in the low-realism condition than in the medium- and high-realism conditions (all p<.001). These results partially supported **[H2]** in the sense that low-realism avatar elicited the lowest body ownership, although there was not significant difference in the strength of body ownership between high- and medium- realism avatars.

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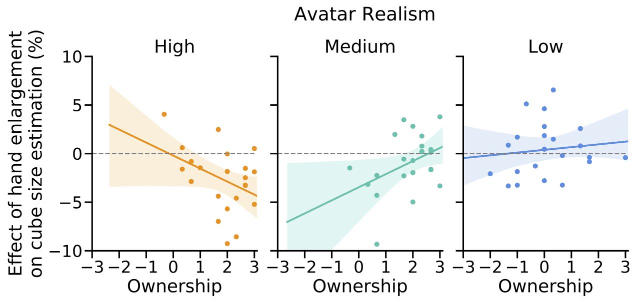

Figure 8: Scatter plots with linear regression lines between the effect of hand enlargement on the estimated cube size and the body ownership scores for each realism level. Translucent bands indicate 95% CIs. 10,000 bootstrap samples were used to estimate each 95% CI.

4.3 Correlation Analysis

To test **[H4]**: the participants with higher scores of body ownership tend to perceive the object size as smaller under the influence of hand enlargement. We examined whether the score of body ownership positively correlates with the degree to which hand enlargement influences the underestimation of the object size. A polyserial correlation analysis, which is used for the data between a quantitative and an ordinal variable, was conducted between the effect of hand enlargement on estimated cube size (see Figure 6) and the scores of body ownership (see Figure 7) among participants for each realism level. As shown in Figure 8, marginally significant weak correlations were found for high- and medium-realism conditions: (High: $\rho = -0.37, p = .07$, Medium: $\rho = 0.39, p = .05$). In contrast, no significant correlation was found for low realism ($\rho = -0.16, p = .45$). These results did not fully support **[H4]** in the sense that a negative correlation was found for the high-realism avatar, as expected (i.e., a positive correlation with the tendency of underestimation), but the opposite was found for medium-realism avatar.

5 Discussion

5.1 Main Results

The main objective of this study was to examine how avatar realism affects perceived object sizes as the size of the virtual hand changes. We found four main results from the experiment. First, the object size was perceived as smaller when the virtual hand size was enlarged only in the case of a highly realistic virtual hand (see Figure 4), which confirmed **[H1]**. Second, the data from the questionnaire (see Figure 7) showed that the low-realism virtual hand produced significantly lower scores of ownership, agency, and location compared with the high- and medium-realism virtual hands. It partially confirmed **[H2]**, considering that the medium-realism avatar did not elicit weaker sense of embodiment than the high-realism avatar. Third, the degree of influence of body size on the object size perception was lower in the low-level realism conditions compared with the highly realistic avatar, which confirmed **[H3]** (see Figure 6). Lastly, a participant's score for body ownership had a weak trend of positive correlation with his/her tendency to perceive the object size as smaller when the virtual hand was enlarged for the high-realism avatar and negative correlation for the medium-realism avatar. The trend is consistent with our hypothesis **[H4]** for the high-realism condition. However, the opposite trend was found for the medium-realism condition. This result did not fully support **[H4]**, even though the support for **[H2]** and **[H3]** indicated that the avatar with low realism provided the weakest body ownership and influence of hand enlargement on size perception. In summary, these findings support the conclusion that avatar realism influences the extent to which the size of a virtual object is perceived based on the size of the virtual hand. Our study provides evidence that self-avatar appearance affects how we perceive not only a virtual body but also virtual spaces. Hence, the effects of the virtual hand appearance on *perception* must be considered to design better virtual experiences that provide precise space perception, even though an avatar can be rendered with any appearance in terms of its *action*.

Our findings indicate that the more realistic the avatar, the more susceptible one's size perception becomes to the difference in the avatar size. At the same time, it also provides a stronger sense of embodiment, including body ownership. This trade-off provides a new insight in the field of 3DUI: we should consider the avatar appearance in scale-sensitive VR applications. Current VR applications often display generic avatars of a certain size, regardless of the user's actual body size, especially when users hold controllers. In such cases, the user recognizes virtual spaces through avatars whose sizes differ from the actual size of the user's body. Consequently, the user's perception of object size is potentially affected. Therefore, in the case of scale-sensitive VR applications, our results indicate the following: if the size of a virtual hand is generic to all users, then it is desirable that the avatar appearance be non-anthropomorphic (e.g., cursors and controllers), which reduces or even eliminates the influence of the avatar size on object size perception, even though it provides a weaker sense of body ownership. In contrast, if the application needs to achieve a strong sense of body ownership and consistent scale perception among users, then it is better for the virtual hand to be realistic and have a personalized size for users.

Our results showed that when the size of the realistic virtual hand was enlarged to 125% of its actual size, the object size was perceived as smaller by approximately 2.64% compared to the size perceived with the veridical virtual hand. In addition, the ANOVA showed that the effect was regardless of the cube size and hysteresis direction. Several previous studies [2, 12, 23] also confirmed that object sizes are perceived as different when realistic avatar sizes are changed in VEs. However, the size of a full-body avatar was nearly halved in the study by Banakou *et al.* [2], and the size of the virtual hand was doubled or halved in the study by Linkenauger *et al.* [23]. In contrast to their studies, our study provides evidence for the first time that even a change of 125% compared to one's own hand size, which sometimes happens when the virtual hand is generic, can influence the object size perception in VEs, even when the only change is in the virtual hand size. Jung *et al.* [12] compared the accuracy of size perception with a personalized video-based hand against a generic virtual hand. This is a likely occurrence in common VR systems. Nevertheless, the cue that contributed to the size estimation is still unclear in their study because several differences existed between the personalized and generic hands other than the appearance, such as the rendering technique (3DCG vs. chroma key composition) and size. Furthermore, the personalized hand size may have contributed to estimating the object size when compared to a generic hand whose size is unrelated to the participant's own hand size because size estimation is performed while observing the hand next to an object, possibly leading to size estimation by inference. In contrast, our results showed that the mere difference in realism modulated the effect of hand size on the object size estimation even without a direct comparison with the hand. Therefore, we provided the evidence that the size of the implicit body representation, altered through the illusion of body ownership, affects object size perception rather than the viewed size of the virtual hands.

Even though the level of realism influenced both the strength of embodiment and the effect of hand enlargement on size perception, the correlation analysis among the participants only showed a marginal significance between them for the high-realism condition. Figure 8 indicates two weak trends: that stronger body ownership for a realistic avatar results in a greater effect of hand enlargement on object size underestimation and vice versa for the medium-realism avatar. As for the high-realism condition, the sense of body owner-

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ship was almost constantly high because of the interactive immersive VR's powerful potential for embodying a virtual realistic avatar, compared to the previous studies [49, 50] that showed the correlation but used visuotactile stimuli. This might cause a ceiling effect and attenuate the correlation among the participants. If a future study finds a clear correlation between the strength of body ownership and the magnitude of the influence of body size on the object size perception, this link could offer an alternative measurement of body ownership in VR. The opposite trend of the medium-realism avatar can be interpreted in reference to the study by Banakou *et al.* [2], which showed that the embodiment of a child avatar resulted in a greater underestimation of the object size than that of an adult avatar scaled to the same height as the child. They attributed their results to the fact that the cognitive mechanism triggered past experiences associated with being younger. They also explained that if the body type was not one that had been coded in memory through past experience, the participants might be influenced by socially and culturally derived expectations of how it would feel to have a specific body type [2]. In our case, it is considered that our expectation of an "iconic avatar-like" perception, which might be rather mechanic, delivered the opposite effect compared with the realistic avatar, as one feels stronger ownership over the iconic avatar. The influence of the semantic aspects of avatars on perception is an interesting subject for future research. The possibilities of a ceiling effect and a semantic effect can also explain the result that despite the strong sense of embodiment with both high- and medium-realism avatars, the effect of hand enlargement on cube size underestimation tended to be weaker with the medium-realism avatar than with the high-realism avatar, although the difference was not significant.

5.2 Limitations

Although our main results showed that the cube size was perceived as smaller for the enlarged realistic virtual hand compared to the veridical hand, the cube sizes tended to be overestimated compared with the actual virtual cube size under any conditions, as shown in Figure 4 and Figure 5. This tendency has also been shown in a previous study [33]. The overestimation bias does not affect our findings because it can be considered a fixed tendency throughout the experiment and we were only interested in the relative values among the conditions. However, it might be useful to investigate the reason for the overestimation bias.

One possible explanation is that the change in the viewing angle relative to the cube caused an overestimation (i.e., the cubes were on the table when estimating their sizes and above the table when carried). Another explanation is that overestimation occurred because of the absence of the virtual hand display when estimating the cube size. Indeed, egocentric distance perception, which is inseparable from size perception, has been shown to be shrunk by approximately 7% when the avatar is not displayed in VEs [20]. Assuming that the cube was perceived as closer when estimating the cube size, it is expected to be overestimated because closer objects would be larger in terms of their retinal sizes. This view also explains the result that the cube sizes were estimated as significantly smaller with the low-realism avatar compared with the medium- and high-realism avatars for the veridical hand size condition; the abstract hand had less impact on shrinkage in distance perception, resulting in smaller overestimation of the cube size. If this is the case, a change in the avatar appearance immediately affects the perceived scale of the VE. One participant mentioned that he noticed the size of the table continually changing during the experiment, supporting this view. Note that in fact the size of the table was constant throughout the experiment. It implies that the designers of VR applications are recommended to avoid switching the display of the avatar and changing its size when consistent-scale perception is required.

5.3 Future Study

This study focused on the unexplored relationship between avatar realism and body-based scaling, i.e., the effect of hand size on object size perception, evidencing that avatar realism affects the way we perceive the size of virtual objects in near space. Nevertheless, we believe that a number of parameters still encourage further research. First, it is necessary to investigate whether the effect can also be verified with larger and further objects that one cannot interact with. We adopted herein a cube as an object that could be operated by hand based on previous research [12, 23]. However, for VR applications involving architectural scenarios, the scale of the whole external environment is more important than the size of a particular object. For example, when users view a large building virtually, they would like to know the scale of the space as a whole. Thus, an interesting subject for future study is whether the perceived object size could be influenced by body size, regardless of the object's type, size, and distance. Studies have shown that the whole-body illusory ownership of a Barbie doll changes size perception, even at large distances [49, 51], and that the eye height affects the distance perception of the dimensions of the overall environment [20]; this is expected at distant spaces as well, but future verification is needed.

Second, the relative impact of avatar realism and size compared to other cues would require exploration. The VE used in this study was a simplified room, not a realistic one. However, object size perception depends on various cues from our surrounding environment, such as depth cues, familiar object sizes, shadows, and viewing angles. A recent study showed that changing a user's eye height alone cannot override robust familiar size cues in a richly detailed VE filled with objects [16] despite a number of previous reports of the effect of an eye height in simple environments [8, 18, 20, 21]. Thus, it is also important to know whether the effect can also be verified in a highly detailed VE filled with many objects capable of providing rich size cues. In addition, the specification of dominant factors for the determination of perceived body size would be required (e.g., what happens when eye height and visual hand size are conflicting).

Lastly, the influence of different types of distortion in body representation other than simple enlargement would be an interesting topic to explore. For example, it will contribute to further characterization of the relationship among them to measure the perceived object size as a function of the avatar size, including the case of shrinkage, according to the avatar representations. Otherwise, it will be useful to consider other cases of distortion of body representation rather than enlargement, which is sometimes caused by a common 3DUI technique, such as the Go–Go interaction [37]. This perhaps causes a phenomenon similar to the remapping of space by active tool use: space previously mapped as far can be remapped as near in the brain [4, 24, 55]. It is also interesting to explore the effect of a tracking device (e.g., controllers vs gestures) and its accuracy. The difference in tracking form influences the degree to which a user's own movement reflects an avatar's movement; thus, it might affect agency and body ownership.

6 Conclusion

This study investigated the unexplored relationship between avatar realism and body-based scaling, i.e., the effect of hand size on object size perception. Our results showed that perceived object sizes are underestimated only when a realistic virtual hand is used in the case where the virtual hand is enlarged (instead of using a veridical hand size). Our findings indicate that the more realistic the avatar is, the stronger is the sense of embodiment including body ownership, which fosters scaling the size of objects using the size of body representation as a fundamental metric. This provides evidence that self-avatar appearances affect how we perceive not only a virtual body but also virtual spaces.

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